OPEN-FILE REPORT 2000-009

SEISMIC HAZARD EVALUATION OF THE CITY AND COUNTY OF SAN FRANCISCO, CALIFORNIA

2000

DEPARTMENT OF CONSERVATION
Division of Mines and Geology

STATE OF CALIFORNIA
GRAY DAVIS
GOVERNOR

THE RESOURCES AGENCY
MARY D. NICHOLS
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
DARRYL YOUNG
DIRECTOR

DIVISION OF MINES AND GEOLOGY
JAMES F. DAVIS, *STATE GEOLOGIST*

OPEN-FILE REPORT 2000-009

SEISMIC HAZARD EVALUATION OF THE CITY AND COUNTY OF SAN FRANCISCO, CALIFORNIA

DIVISION OF MINES AND GEOLOGY'S PUBLICATION SALES OFFICES:

Southern California Regional Office
655 S. Hope Street, Suite 700
Los Angeles, CA 90017
(213) 239-0878

Publications and Information Office
801 K Street, MS 14-31
Sacramento, CA 95814-3531
(916) 445-5716

Bay Area Regional Office
185 Berry Street, Suite 210
San Francisco, CA 94107-1728
(415) 904-7707

CONTENTS

PREFACE vii

INTRODUCTION 1

SECTION 1 LIQUEFACTION EVALUATION REPORT Liquefaction Zones in the City and County of San Francisco, California 2

PURPOSE 2

Background 3

Scope and Limitations 3

PART I 4

STUDY AREA LOCATION AND PHYSIOGRAPHY 4

GEOLOGIC CONDITIONS 4

GROUND-WATER CONDITIONS 6

PART II 7

EVALUATING LIQuEFACTION POTENTIAL 7

LIQUEFACTION OPPORTUNITY 7

LIQUEFACTION SUSCEPTIBILITY 8

LIQUEFACTION ZONES 9

ACKNOWLEDGMENTS 11

REFERENCES 12

SECTION 2 EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT Earthquake-Induced Landslide Zones in the City and County of San Francisco, California 16

PURPOSE 16

Background 17

Scope and Limitations 17

PART I 18

STUDY AREA LOCATION AND PHYSIOGRAPHY 18

GEOLOGIC CONDITIONS 18

PART II 22

EARTHQUAKE-INDUCED LANDSLIDE GROUND SHAKING OPPORTUNITY 22

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL 24

EARTHQUAKE-INDUCED LANDSLIDE ZONE 26

ACKNOWLEDGMENTS 27

REFERENCES 27

AIR PHOTOS 30

APPENDIX A Source of Rock Strength Data 30

SECTION 3 GROUND SHAKING EVALUATION REPORT Potential Ground Shaking in the City and County of San Francisco, California 31

PURPOSE 31

EARTHQUAKE HAZARD MODEL 32

APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS 36

USE AND LIMITATIONS 36

REFERENCES 39

ILLUSTRATIONS

Figure 2.1. Yield Acceleration vs. Newmark Displacement for the Southern California Edison Lucerne strong-motion record from the 28 June 1992 Landers, California earthquake. 24

Figure 3.1. City and County of San Francisco and portions of adjacent quadrangles, 10% exceedance in 50 years peak ground acceleration (g)—Firm rock conditions. 33

Figure 3.2. City and County of San Francisco and portions of adjacent quadrangles, 10% exceedance in 50 years peak ground acceleration (g)—Soft rock conditions. 34

Figure 3.3. City and County of San Francisco and portions of adjacent quadrangles, 10% exceedance in 50 years peak ground acceleration (g)—Alluvium conditions. 35

Figure 3.4. City and County of San Francisco and portions of adjacent quadrangles, 10% exceedance in 50 years peak ground acceleration—Predominant earthquake. 37

Table 2.1. Summary of the Shear Strength Statistics for the City and County of San Francisco. 20

Table 2.2. Summary of the Shear Strength Groups for the City and County of San Francisco. 21

Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in San Francisco. Shaded area indicates hazard potential levels included within the hazard zone. 26

Plate 1.1. Borehole log data locations, City and County of San Francisco

Plate 1.2. Historically highest ground-water contours, City and County of San Francisco

Plate 2.1. Landslide inventory and shear test sample locations, City and County of San Francisco

PREFACE

With the increasing public concern about the potential for destructive earthquakes in northern and southern California, the State Legislature passed the Seismic Hazards Mapping Act in 1990. The purpose of the Act is to protect the public from the effects of strong ground shaking, liquefaction, landslides or other ground failure, and other hazards caused by earthquakes. The program and actions mandated by the Seismic Hazards Mapping Act closely resemble those of the Alquist-Priolo Earthquake Fault Zoning Act (which addresses only surface fault-rupture hazards) and are outlined below:

1. **The State Geologist** is required to delineate the various "seismic hazard zones."

2. **Cities and Counties**, or other local permitting authorities, must regulate certain development "projects" within the zones. They must withhold the development permits for a site within a zone until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans.

3. **The State Mining and Geology Board (SMGB)** provides additional regulations, policies, and criteria to guide cities and counties in their implementation of the law. The SMGB also provides criteria for preparation of the Seismic Hazard Zone Maps (Web site http://www.consrv.ca.gov/dmg/shezp/zoneguid/) and for evaluating and mitigating seismic hazards.

4. **Sellers (and their agents)** of real property within a mapped hazard zone must disclose at the time of sale that the property lies within such a zone.

As stated above, the Act directs the State Geologist, through the Division of Mines and Geology (DMG) to delineate seismic hazard zones. Delineation of seismic hazard zones is conducted under criteria established by the Seismic Hazards Mapping Act Advisory Committee and its Working Groups and adopted by the California SMGB.

The Official Seismic Hazard Zone Maps, released by DMG, which depict zones of required investigation for liquefaction and/or earthquake-induced landslides, are available from:

BPS Reprographic Services
149 Second Street
San Francisco, California 94105
(415) 512-6550

Seismic Hazard Evaluation Reports, released as Open-File Reports (OFR), summarize the development of the hazard zone map for each area and contain background documentation for use by site investigators and local government reviewers. These Open-File Reports are available for reference at DMG offices in Sacramento, San Francisco, and Los Angeles. Copies of the reports may be purchased at the Sacramento, Los Angeles, and San Francisco offices. In addition, the Sacramento office offers prepaid mail order sales for all DMG OFRs. **NOTE: The Open-File Reports are not available through BPS Reprographic Services.**

DIVISION OF MINES AND GEOLOGY OFFICES

Geologic Information and Publications Office
801 K Street, MS 14-33
Sacramento, CA 95814-3532
(916) 445-5716

Bay Area Regional Office
185 Berry Street, Suite 210
San Francisco, CA 94107-1728
(415) 904-7707

Southern California Regional Office
655 S. Hope Street, Suite 700
Los Angeles, CA 90017
(213) 239-0878

WORLD WIDE WEB ADDRESS

Seismic Hazard Evaluation Reports and additional information on seismic hazard zone mapping in California are available on the Division of Mines and Geology's Internet homepage: http://www.consrv.ca.gov/dmg/shezp/

INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, Division of Mines and Geology (DMG) to delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (1997; also available on the Internet at http://www.consrv.ca.gov/dmg/pubs/sp/117/).

The Act also directs SMGB to appoint and consult with the Seismic Hazards Mapping Act Advisory Committee (SHMAAC) in developing criteria for the preparation of the seismic hazard zone maps. SHMAAC consists of geologists, seismologists, civil and structural engineers, representatives of city and county governments, the state insurance commissioner and the insurance industry. In 1991 SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria provide detailed standards for mapping regional liquefaction hazards. They also directed DMG to develop a set of probabilistic seismic maps for California and to research methods that might be appropriate for mapping earthquake-induced landslide hazards.

In 1996, working groups established by SHMAAC reviewed the prototype maps and the techniques used to create them. The reviews resulted in recommendations that the 1) process for zoning liquefaction hazards remain unchanged and that 2) earthquake-induced landslide zones be delineated using a modified Newmark analysis.

This Seismic Hazard Evaluation Report summarizes the development of the hazard zone map for each area. The process of zoning for liquefaction uses a combination of Quaternary geologic mapping, historic high-water-table information, and subsurface geotechnical data. The process for zoning earthquake-induced landslides incorporates earthquake loading, existing landslide features, slope gradient, rock strength, and geologic structure. Probabilistic seismic hazard maps, which are the underpinning for delineating seismic hazard zones, have been prepared for peak ground acceleration, mode magnitude, and mode distance with a 10% probability of exceedance in 50 years (Petersen and others, 1996) in accordance with the mapping criteria.

This evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils and earthquake-induced landslides in the City and County of San Francisco (scale 1:24,000).

SECTION 1
LIQUEFACTION EVALUATION REPORT

Liquefaction Zones in the City and County of San Francisco, California

By
Mark J. DeLisle

California Department of Conservation
Division of Mines and Geology

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, Division of Mines and Geology (DMG) to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the seismic zone maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (1997; also available on the Internet at http://www.consrv.ca.gov/dmg/pubs/sp/117/).

This evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the City and County of San Francisco. This section and Section 2 addressing earthquake-induced landslides, are part of a series that will summarize development of similar hazard zone maps in the state (Smith, 1996). Additional information on seismic hazards zone mapping in California can be accessed on DMG's Internet homepage: http://www.consrv.ca.gov/dmg/shezp/

BACKGROUND

Liquefaction-induced ground failure has historically been a major cause of earthquake damage in northern California. During the 1989 Loma Prieta and 1906 San Francisco earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the San Francisco Bay area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated granular sediment within the upper 40 feet of the ground surface. These geological and ground-water conditions are widespread in the San Francisco Bay area, most notably in some densely populated valley regions and alluviated floodplains. In addition, the opportunity for strong ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard especially in areas marginal to the San Francisco Bay in general, as well as in the City and County of San Francisco.

SCOPE AND LIMITATIONS

Evaluation for potentially liquefiable soils is generally confined to areas covered by Quaternary sedimentary deposits. Such areas consist mainly of low-lying shoreline regions, alluviated valleys, and floodplains, and alluvial fans. This liquefaction evaluation is based on predicted earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and ground-water depth data. These data are gathered from multiple sources and the quality varies. Although evaluation of data used in this study was rigorous, the state of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data obtained from outside sources.

Liquefaction zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, liquefaction zone maps identify areas where the potential for liquefaction exists. They do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth and thickness of liquefiable sediments, depth to ground water, rate of drainage, slope gradient, proximity to free-face conditions, and intensity and duration of ground shaking. These factors must be evaluated on a site-specific basis to determine the potential for ground failure at any given project site.

Information developed in the study is presented in two parts: physiographic, geologic, and hydrologic conditions in PART I, and liquefaction potential, opportunity, susceptibility, and zoning evaluations in PART II.

PART I

STUDY AREA LOCATION AND PHYSIOGRAPHY

The City and County of San Francisco lie in the western part of the Coast Ranges along the central California coast. The study area is a peninsula bound by the Pacific Ocean on the west and San Francisco Bay on the north and east. The prominent northwesterly structural and topographic trend of the northern Coast Ranges is not evident in the city except for minor hills and valleys. The present topography is the result of erosion of Mesozoic Franciscan Complex rocks of varying hardness with deposits of windblown sand that locally mantle the bedrock exposures. Quaternary tectonism, marine and estuarine deposition, and artificial fill (man-made land) have also contributed to the development of the current topography of the study area.

GEOLOGIC CONDITIONS

Surface Geology

The City and County of San Francisco are located within the southern portion of the San Francisco North, western portion of the Oakland West, northern portion of the San Francisco South and northwestern portion of the Hunters Point 7.5-minute U. S. Geological Survey topographic quadrangles. These quadrangles have been mapped in detail by Radbruch (1957), Bonilla (1971), Schlocker (1974), Helley and others (1979), Helley and Graymer (1997) and Knudsen and others (1997).

The geologic formations on the peninsula fall into three groups, which differ greatly in age; older bedrock, Tertiary strata, and surficial deposits. The older bedrock consists of Franciscan Complex sedimentary rocks, greenstone, various other metamorphic and sheared rocks and associated serpentinite, and gabbro-diabase intrusions. Tertiary rocks crop out in the sea cliffs along the southwestern part of the county. Tilted marine strata of the Plio-Pleistocene Merced Formation (QTm) (Clifton and Hunter, 1987) lie unconformably below Pleistocene Colma Formation (Qco) and late Pleistocene and Holocene dune sand (Qs). The surficial deposits of the city consist of colluvium in the hills with broad valleys that are underlain by unconsolidated material. Unconsolidated late Pleistocene and Holocene deposits are primarily sand, modern beach deposits (Qm), dune sand (Qs), and undifferentiated Quaternary deposits (Qa). Also included is bay mud (Qhbm) (Joyner, 1982), landslides, rubbly slope debris, and ravine fill. These units were deposited on the old topographic surface of Franciscan Complex rocks (Bonilla, 1964) or Pleistocene deposits. Artificial fill (af) is also widespread in the area.

Yerba Buena Island is a natural island composed of Franciscan Complex sandstone, colluvium, and artificial fill (af). Treasure Island consists entirely of sandy and silty artificial fill.

The Quaternary geology was compiled from published geologic maps of Radbruch (1957), Radbruch and Schlocker (1958), Bonilla (1971), Schlocker (1974), and Knudsen and others (1997). Slight modifications to the boundaries of some Quaternary units were made based on subsurface information from boreholes and examination of old U.S. Coast Survey (1851, 1857a, 1857b, 1867) topographic maps. These old topographic maps are particularly useful in determining areas of artificial fill. Modifications to the maps were made (using computers) by matching the pre-existing coastline and old drainage patterns with present-day topography, which permitted identification of previously unknown fills.

The Quaternary deposits evaluated for liquefaction zoning are artificial fills (af), modern beach deposits (Qm), dune sand (Qs), and undifferentiated Quaternary deposits (Qa).

Subsurface Geology and Geotechnical Characteristics

Borehole information was used to determine general subsurface conditions. Water depths, local site stratigraphy, and standard penetration tests (SPT) were used to characterize the geotechnical properties of each stratigraphic unit. Geotechnical data were collected from more than 600 sites, where one or more holes had been drilled. Borehole logs from these sites were collected, after inspecting several thousand files, from CalTrans, the City of San Francisco's Bureau of Building Inspection, Clean Water Program, Bureau of Engineering, and Department of City Planning. Plate 1.1 shows the locations of boreholes used in this study.

Several geologic cross sections were constructed across the study area using areal-geology and borehole-lithology information to make subsurface stratigraphic correlations. On the western side of the peninsula, the dune sand deposits (Qs) extend from west of Lake Merced, where they unconformably overlie the Pleistocene Colma Formation, to the north. At Point Lobos and the Presidio the dune sand overlies the Franciscan Complex. The thickness of the dune sand ranges from zero to nearly 100 feet; its relative density grades from loose near the surface to dense and very dense with depth. The dune sand is Holocene to possibly Pleistocene. The Colma Formation lies on Franciscan Complex rocks and consists of interbedded dense sand, silty sand, clayey sand, and stiff clay. The Colma Formation originated in shallow marine, estuarine, and alluvial environments.

On the eastern side of the peninsula, the dune sand deposits extend from the bay on the north to an area south of Market Street. On the north, the dune sand overlies probable Colma Formation; whereas, on the south, it overlies undivided Quaternary deposits (Qa) and interfingers with the Holocene bay mud (Qhbm). Bay mud underlies areas of artificial fill (af) along fringes of the bay between the present and past (historical) shorelines. For example, one borehole near China Basin between 4th and 5th streets penetrated 125 feet of bay mud (Qhbm). There is artificial fill (af) to 60 feet in a borehole south of Market Street along the Embarcadero. The Qa overlies the Colma Formation and consists of stiff clay, clayey sand, silty sand, and sand. The Qa appears to consist of late Pleistocene to Holocene alluvial, estuarine, and, possibly, eolian deposits.

Geotechnical properties of unconsolidated deposits

From a geotechnical perspective, dune sand is fine- to medium-grained and well sorted, with less than 5% fines by weight. Normalized blow count values, $(N_1)_{60}$, for 597 dune sand samples (Table 1.1) have a mean value of 29. Where the ground is saturated, less than 1% of the samples has values lower than 15 and the mean $(N_1)_{60}$ is 39, indicating that this sand may densify rapidly when saturated. Samples of undifferentiated Quaternary deposits were grouped into two categories: sand (SP in the Unified Soil Classification) and silty sand (SM). The 129 well-sorted sand (SP) samples have a mean $(N_1)_{60}$ value of 43, and the 134 samples of silty sand (SM) have a mean $(N_1)_{60}$ of 40. A summary of the Quaternary units is shown in Table 1. 1.

GEOLOGIC DATA		DRY UNIT WEIGHT			STANDARD PENETRATION RESISTANCE		
		(PCF)			(blows/foot)*		
Geologic Unit	Soil Class	Low Range (lower 10%)	Average (40-60%)	High Range (upper 10%)	Low Range (lower 10%)	Most Common Range (40-60%)	High Range (upper 10%)
Dune sand	SP	92-98	105	112-124	3-9	20-28	54-128
Undiff. Quat.	SP	93-101	107	115-123	6-14	33-48	77-136
Undiff. Quat.	SM	97-104	110	118-124	6-11	30-38	75-133

*****Where the sampler diameter, hammer size or drop distance differed from those specified for an SPT, recorded blow counts were converted to the equivalent of SPT blow counts. The actual and converted SPT blow counts were normalized using a common effective overburden pressure and adjusted for equipment and operational procedures using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count, $(N_1)_{60,}$ is used in Table 1.1

Table 1.1 Summary of geotechnical characteristics for Quaternary geological units evaluated for liquefaction zoning in the City and County of San Francisco.

GROUND-WATER CONDITIONS

A ground-water evaluation of the area was performed in order to determine historically shallow ground-water levels in the City and County of San Francisco. Areas characterized by historical ground water or perched water less than 40 feet below the ground surface are considered for the purposes of liquefaction zoning. For this evaluation, a ground-water surface map, showing the historically highest ground water, was prepared. Soils above the mapped water surface are considered non-liquefiable. Preparation of the map incorporated a study for San Francisco County by Bartell (1913) using water depths from approximately 700 water wells. Water depths recorded on CalTrans borehole logs, U.S. Geological Survey (USGS) monitoring wells (Phillips and others, 1993), California Department of Water Resources water-well logs, and borehole logs from soils reports and other geotechnical investigations from 1955-92 were collected from various agencies. Data were plotted and tabulated, and ground-water depths were contoured (Plate 1.2). Most ground-water maps show the actual water table at a particular time, whereas this map depicts a hypothetical ground-water table. These unpublished ground-water maps are used during the liquefaction analysis.

PART II

EVALUATING LIQUEFACTION POTENTIAL

Liquefaction occurs in water-saturated sediments during moderate to great earthquakes. Liquefied sediments are characterized by a loss of strength and may fail, causing damage to buildings, bridges, and other such structures. A number of methods for mapping liquefaction hazard have been proposed; Youd (1991) highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of susceptibility units, and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce liquefaction potential. Liquefaction susceptibility is a function of the capacity of sediments to resist liquefaction and liquefaction opportunity is a function of the seismic ground shaking intensity. The application of the Seed Simplified Procedure (Seed and Idriss, 1971) for evaluating liquefaction potential allows a quantitative characterization of susceptibility of geologic units. Tinsley and others (1985) applied a combination of the techniques used by Seed and others (1983) and Youd and Perkins (1978) for mapping liquefaction hazards in the Los Angeles region. The method applied in this study for evaluating liquefaction potential is similar to that of Tinsley and others (1985), combining geotechnical data analyses, and geologic and hydrologic mapping, but follows criteria adopted by the California State Mining and Geology Board (in press).

LIQUEFACTION OPPORTUNITY

According to the criteria adopted by the California State Mining and Geology Board (in press), liquefaction opportunity is a measure, expressed in probabilistic terms, of the potential for ground shaking strong enough to generate liquefaction. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. The minimum level of seismic excitation to be used for such purposes will be that level of peak ground acceleration (PGA) with a 10% probability of exceedance over a 50-year period. Earthquakes that could produce ground shaking levels great enough to trigger liquefaction within the project area are likely to be associated with the San Andreas Fault, which intersects the coast approximately 2.5 miles south of the study area, or the Hayward Fault, which lies 10 miles east of San Francisco. The Working Group on California Earthquake Probabilities (1999) estimates about a 70% chance for at least one magnitude 6.7 or greater earthquake in the San Francisco Bay region in the next 30 years.

For the City and County of San Francisco area, peak accelerations of 0.5 g to 0.86 g resulting from an earthquake of magnitude 7.9 were used for liquefaction analyses. The PGA and magnitude values were based on de-aggregation of the probabilistic hazard at the 10% in 50-year hazard level (Petersen and others, 1996). See the ground motion portion (Section 3) of this report for further details. Due to this anticipated high shaking hazard, the susceptibility maps are essentially the same as the liquefaction potential maps.

LIQUEFACTION SUSCEPTIBILITY

Liquefaction susceptibility reflects the relative resistance of soils to loss of strength when subjected to ground shaking. Primarily, physical properties and conditions of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth govern the degree of resistance. Soils that lack resistance (susceptible soils) are typically saturated, loose sandy sediments. Soils resistant to liquefaction include all soil types that are dry or sufficiently dense. Cohesive soils are generally not considered susceptible to liquefaction.

DMG's map inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps, cross-sections, geotechnical test data, geomorphology, and ground-water hydrology. Soil-property and soil-condition factors such as type, age, texture, color, and consistency, along with historic depths to ground water are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on similar soil observations, findings can be related in terms of the map units.

Quantitative Liquefaction Analysis

DMG performs quantitative analyses of geotechnical data to evaluate liquefaction potential using the Seed Simplified Procedure (Seed and Idriss, 1971, 1982; Seed and others, 1983, 1984, 1985; National Research Council, 1985; Seed and Harder, 1990; Youd and Idriss, 1997). This procedure calculates soil resistance to liquefaction, expressed in terms of cyclic resistance ratio (CRR) based on standard penetration test results, ground-water level, soil density, moisture content, soil type, and sample depth. CRR values are then compared to calculated earthquake-generated shear stresses, expressed in terms of cyclic stress ratio (CSR). The factor of safety (FS) relative to liquefaction is: FS=CRR/CSR. FS, therefore, is a quantitative measure of liquefaction potential. Generally, a factor of safety of 1.0 or less, where CSR equals or exceeds CRR, indicates the presence of potentially liquefiable soil. DMG uses FS, as well as other considerations such as slope, free face conditions, and thickness and depth of potentially liquefiable soil, to construct liquefaction potential maps, which then directly translate to Zones of Required Investigation.

More than 400 of the borehole logs collected in the City and County of San Francisco include blow-count data from SPTs or from penetration tests that allow reasonable blow count translations to SPT-equivalent values. Non-SPT values, such as those resulting from the use of 2-inch or 2 1/2-inch inside diameter ring samplers, were translated to

SPT-equivalent values if reasonable factors could be used in conversion calculations. SPT-equivalent values vary in reliability and are weighted and used in a more qualitative manner. Few borehole logs, however, include all of the information (soil density, moisture content, sieve analysis, etc.) required for an ideal Seed Simplified Analysis. For boreholes having acceptable penetration tests, liquefaction analysis is performed using logged density, moisture, and sieve test values, or using average test values of similar materials.

Overall Liquefaction Susceptibility

The propensity for a deposit to fail was characterized by grouping deposits into high, moderate, low, and very low categories (Table 1.2) based on depth to ground water, type of sediment, texture, and stiffness, as determined by the SPT. The highest susceptibility is found in areas where dune sand (Qs) is saturated at depths shallower than 10 feet, in areas of artificial fill, and beach deposits.

Also, historical occurrences of liquefaction during the 1906 San Francisco earthquake indicate a pronounced lack of liquefaction in the undifferentiated Quaternary deposits (Qa) or the dune sand (Qs) where the depth to ground water is more than 10 feet. There is one reported occurrence of ground failure on 48th Avenue between K and N streets (currently 48th Avenue between Kirkham and Noriega streets) in dune sand where depth to water is less than 10 feet. This description (Lawson and others, 1908) does indicate the area was developed prior to 1906; consequently, it may have been the fill material that failed.

Water depth	High	Moderate	Low	Very Low
10 ft	af, Qm, Qs	Qa		bedrock, Qcl
10-30 ft	af	Qs	Qa	bedrock, Qcl
30-50 ft	af	Qs	Qa	bedrock, Qcl

Table 1.2. Liquefaction susceptibility of Quaternary sedimentary units and artificial fill.

LIQUEFACTION ZONES

Criteria for Zoning

The areas underlain by late Quaternary geologic units were included in liquefaction zones using the criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the California State Mining and Geology Board (in press). Under those criteria, liquefaction zones are areas meeting one or more of the following:

1. Areas known to have experienced liquefaction during historic earthquakes.

2. All areas of uncompacted fills containing liquefaction susceptible material that are saturated, nearly saturated, or may be expected to become saturated.

3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable.

4. Areas where existing geotechnical data are insufficient**.**

In areas of limited or no geotechnical data, susceptibility zones may be identified by geologic criteria as follows:

a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the water table is less than 40 feet below the ground surface; or

b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the historic high water table is less than or equal to 30 feet below the ground surface; or

c) Areas containing soil deposits of latest Pleistocene age (between 11,000 years and 15,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.30 g and the historic high water table is less than or equal to 20 feet below the ground surface.

Application of SMGB criteria for liquefaction zoning in the City and County of San Francisco is summarized below.

Areas of Past Liquefaction

In the study area, historic occurrences of liquefaction are documented by Lawson and others, (1908), Youd and Hoose (1976; 1978), Bennet (1990), Seed and others (1990), Harding Lawson Associates and others (1991a; 1991b), Pease and others (1992); Pease and O'Rourke (1993), Bardet and Kapuskar (1993) and Tinsley and others (1998). All areas of historic liquefaction are included in the hazard zone.

Artificial Fills

Artificial fill (af) has been placed at many localities during the development of San Francisco. Many of the historic occurrences of ground failure related to liquefaction are associated with artificial fill. These fills are composed of various materials compacted to varying densities. Pease and others (1992) in a study of the Marina District using borehole and SPT information, found hydraulic fill has a mean $(N_1)_{60}$ of 6, land-tipped fill has a mean $(N_1)_{60}$ of 14, whereas natural sand deposits have a mean $(N_1)_{60}$ of 26. Due to the variability of the material and the haphazard distribution of that material in artificial fill deposits, a site-specific investigation is necessary to determine if a hazard exists. All fill material that is saturated or may become saturated is included within the hazard zone.

Areas with Sufficient Existing Geotechnical Data

Geotechnical data were collected from more than 600 sites where one or more boreholes were drilled. Borehole logs were collected from files of CalTrans and the City of San Francisco's Bureau of Building Inspection, Clean Water Program, Bureau of Engineering, and Department of City Planning.

The undifferentiated Quaternary deposits (Qa) and the dune sand (Qs) deposits were analyzed and characterized, as discussed previously under "Liquefaction Susceptibility." The hazard zone boundary is defined by the susceptibility category with no modification by ground shaking, because over the entire area ground shaking exceeds the critical level necessary to induce liquefaction.

Areas with Insufficient Existing Geotechnical Data

No borehole information was found for modern beach deposits (Qb). However, by the loose, saturated-sand nature of the material in these deposits, they are included within the hazard zone.

ACKNOWLEDGMENTS

Many individuals from many different agencies provided useful information. It is impossible to list all that assisted in the process. Key individuals are Catherine Bauman, San Francisco Department of City Planning, who formed an oversight committee in order to keep the city engineers informed and involved with our program, and the staff of the San Francisco Department of Building Inspection, who granted access to the city's geotechnical files.

Many DMG staff helped to prepare the hazard map. Bob Moskovitz, Teri McGuire, Scott Shepherd and Barbara Wanish provided GIS operations support, and designed and plotted the graphic displays associated with the liquefaction zone map and this report. Robert Darragh, Dames and Moore formed a peer-review committee, which consisted of Henry Taylor, Faiz Makdisi, Keith Kelson, Tom Holzer, James Gamble, Lelio Mejia, Frank Rollo, and Dick Tait for review of the San Francisco North Quadrangle hazard map.

Finally, I wish to thank Julie Monet, who collected much of the borehole data, entered it in a database and assisted in the analysis for the San Francisco South Quadrangle.

REFERENCES

Bardet, J.P. and Kapuskar, M., 1993, Liquefaction sand boils in San Francisco during 1989 Loma Prieta earthquake: Journal of Geotechnical Engineering, v. 119, no. 3, p. 543-562.

Bartell, M.J., 1913, Report on the underground water supply of San Francisco County: San Francisco Department of Public Works, 157 p.

Bennett, M.G., 1990, Ground deformation and liquefaction of soil in the Marina District: U.S. Geological Survey Open-File Report 90-253, p. 44-79

Bonilla, M.G., 1964, Bedrock-surface map of the San Francisco South Quadrangle, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-334, scale 1:31,680.

Bonilla, M.G., 1971, Preliminary geologic map of the San Francisco South Quadrangle and part of the Hunter's Point Quadrangle, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-311, 2 sheets, scale 1:24,000.

California State Mining and Geology Board, 1997, Guidelines for evaluating and mitigating seismic hazards in California: California Department of Conservation, Division of Mines and Geology, Special Publication 117, 74 p.

California State Mining and Geology Board, in press, Criteria for delineating seismic hazard zones: California Department of Conservation, Division of Mines and Geology, Special Publication 118, 21 p.

Clifton, H.E. and Hunter, R.E., 1987, The Merced Formation and related beds: a mile-thick succession of late Cenozoic coastal and shelf deposits in the seacliffs of San Francisco, California: Geological Society of America Centennial Field Guide Cordilleran Section, p. 257-262.

Harding Lawson Associates, Dames and Moore, Kennedy, Jenks, Chilton, and EQE Engineering, 1991a, Liquefaction study, North Beach, Embarcadero waterfront, South Beach, and Upper Mission Creek area, San Francisco, California: Harding Lawson Associates, San Francisco, California Report No. 17592.041.04.

Harding Lawson Associates, Dames and Moore, Kennedy, Jenks, Chilton, and EQE Engineering, 1991b, Marina District and Sullivan Marsh liquefaction study, San Francisco, California: Harding Lawson Associates, San Francisco, California Report No. 17592.041.04.

Helley, E.J., Lajoie, K.R., Spangle, W.E. and Blair, M.L., 1979, Flatland deposits of the San Francisco Bay Region, California-their geology and engineering properties, and their importance to comprehensive planning: U.S. Geological Survey Professional Paper 943, 88 p.

Helley, E.J. and Graymer, R.W., 1997, Quaternary geology of Alameda County, and parts of Contra Costa, Santa Clara San Mateo, San Francisco, Stanislaus and San Joaquin counties, California: A digital database: U.S. Geological Survey Open File Report 97-97.

Knudsen, K.L., Noller, J.S., Sowers, J.M. and Lettis, W.R., 1997, Map showing Quaternary geology and liquefaction susceptibility, San Francisco, California, 1:100,000 Sheet: Final Technical Report: National Earthquake Hazards Reduction Program, U.S. Geological Survey, FY95 Award Number 1434-94-G-2499, p.1-20

Joyner, W.B., 1982, Map showing the 200-foot thickness contour of surficial deposits and the landward limit of Bay Mud deposits of San Francisco, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1376, scale 1:24,000.

Lawson, A.C. and others, 1908, The California earthquake of April 18, 1906: Report of the State Investigative Commission, Carnegie Institute, Washington, D.C.

National Research Council, 1985, Liquefaction of soils during earthquakes: National Research Council Special Publication, Committee on Earthquake Engineering, National Academy Press, Washington, D.C., 240 p.

Pease, J.W. and O'Rourke, T.D., 1993, Liquefaction hazards in the Mission District and south of Market areas, San Francisco, California: Prepared under U.S. Geological Survey Grant No. 14-08-0001-G2128.

Pease, J.W., O’Rourke, T.D. and Stewart, H.E., 1992, Post-liquefaction consolidation and lifeline damage in the Marina District after the 1989 Loma Prieta earthquake, *in* Hamada, Masanori and O'Rourke, T.D., *editors*, Proceedings from the Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, v. 1: National Center for Earthquake Engineering Research, State University of New York at Buffalo, New York, Technical Report NCEER-92-0019.

Petersen, M.D., Cramer, C.H., Bryant, W.A., Reichle, M.S. and Toppozada, T.R., 1996, Preliminary seismic hazard assessment for Los Angeles, Ventura, and Orange counties, affected by the 17 January 1994 Northridge earthquake: Bulletin of the Seismological Society of America, v. 86, no. 1B, p. S247-S261.

Phillips, S.P., Hamlin, S.N. and Yates, E.B., 1993, Geohydrology, water quality, and estimation of ground-water recharge in San Francisco, California, 1987-92: U.S. Geological Survey Water-Resources Investigations Report 93-4019.

Radbruch, D.H., 1957, Areal and engineering geology of the Oakland West Quadrangle, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-239, scale 1:24,000.

Radbruch, D.H. and Schlocker, Julius, 1958, Engineering geology of Islais Creek basin, San Francisco, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-264.

Schlocker, Julius, 1974, Geology of the San Francisco North Quadrangle, California: U.S. Geological Survey Professional Paper 782, 109 p.

Seed, H.B. and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquefaction potential: Journal of the Soil Mechanics and Foundations Division of ASCE, v. 97: SM9, p. 1,249-1,273.

Seed, H.B. and Idriss, I.M., 1982, Ground motions and soil liquefaction during earthquakes: Monograph Series, Earthquake Engineering Research Institute, Berkeley, California, 134 p.

Seed, H.B., Idriss, I.M. and Arango, Ignacio, 1983, Evaluation of liquefaction potential using field performance data: Journal of Geotechnical Engineering, v. 109, no. 3, p. 458-482.

Seed, H.B., Tokimatsu, Kohji, Harder, L.F. and Chung, R.M., 1984, The influence of SPT procedures in soil liquefaction resistance evaluations: Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, Report No. UCB/EERC-84/15.

Seed, H.B., Tokimatsu, Kohji, Harder, L.F. and Chung, R.M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, v. 111, no. 12, p. 1,425-1,445.

Seed, R.B. and Harder, L.F., 1990, SPT-based analysis of cyclic pore pressure generation and undrained residual strength: Proceedings of the H. Bolton Seed Memorial Symposium, v. 2, p. 351-376.

Seed, R.B., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Harder, L.F., Jr. and Power, M.S., 1990, Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake: Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, Report No. UCB/EERC-90/05.

Smith, T.C., 1996, Preliminary maps of seismic hazard zones and draft guidelines for evaluating and mitigating seismic hazards: California Geology, v. 49, no. 6, p. 147-150.

Tinsley, J.C., Egan, J.A., Kayen, R.E., Bennett, M.J., Kropp, A. and Holzer, T.L., 1998, Appendix: Maps and descriptions of liquefaction and associated effects *in* Holzer, T.L., *editor*, The Loma Prieta, California earthquake of October 17, 1989 – Liquefaction: U.S. Geological Survey Professional Paper 1551-B, p. B287-314.

Tinsley, J.C., Youd, T.L., Perkins, D.M. and Chen, A.T.F., 1985, Evaluating liquefaction potential, *in* Ziony, J.I., *editor*, Evaluating earthquake hazards in the Los Angeles region -- An earth science perspective: U.S. Geological Survey Professional Paper 1360, p. 263-316.

U.S. Coast Survey, 1851, South shore Golden Gate from Point Lobos to San Francisco, California: Surveyed by R.J. Cutts.

U.S. Coast Survey, 1857a, Revisionary survey for the determination of the lighthouses and defense works of the harbor of San Francisco, California: Register No. 663.

U.S. Coast Survey, 1857b, City of San Francisco and its vicinity, California: Register No. 687.

U.S. Coast Survey, 1867, Map showing part of land approaches to city of San Francisco, California for use of Engineer Department U.S. Army: Register No. 1059.

Working Group on California Earthquake Probabilities, 1999, Understanding earthquake hazards in the San Francisco Bay region, California: U.S. Geological Survey Fact Sheet-152-99, 4 p.

Youd, T.L., 1991, Mapping of earthquake-induced liquefaction for seismic zonation: Earthquake Engineering Research Institute, Proceedings, Fourth International Conference on Seismic Zonation, v. 1, p. 111-138.

Youd, T.L. and Hoose, S.N., 1976, Liquefaction during the 1906 San Francisco earthquake: Journal of the Geotechnical Engineering Division, v. 102, no. GT5, May, p. 425-440.

Youd, T.L. and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, U.S. Government Printing Office, Washington, D.C., 178 p.

Youd, T.L. and Idriss, I.M., 1997, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: Technical Report NCEER-97-0022, 277 p.

Youd, T.L. and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, v. 104, p. 433-446.

SECTION 2
EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT

Earthquake-Induced Landslide Zones in the City and County of San Francisco, California

By
Rick I. Wilson, Mark O. Wiegers, and Timothy P. McCrink

California Department of Conservation
Division of Mines and Geology

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, Division of Mines and Geology (DMG) to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (1997; also available on the Internet at http://www.consrv.ca.gov/pubs/sp/117/).

This evaluation report summarizes seismic hazard zone mapping for earthquake-induced landslides in the City and County of San Francisco (scale 1:24,000). This section and Section 1 addressing liquefaction, are part of a series that will summarize development of similar hazard zone maps in the state (Smith, 1996). Additional information on seismic hazard zone mapping in California can be accessed on DMG's Internet homepage: http://www.consrv.ca.gov/dmg/shezp/

BACKGROUND

Landslides triggered by earthquakes have historically been a major cause of earthquake damage. Landslides triggered by the 1971 San Fernando, 1989 Loma Prieta and 1994 Northridge earthquakes were responsible for destroying or damaging numerous homes and other structures, blocking major transportation corridors, and damaging various types of lifeline infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, and loose soils, and on or adjacent to existing landslide deposits. These geologic and terrain conditions exist in many parts of California, most notably in hilly areas already developed or currently undergoing development. In addition, the opportunity for strong earthquake ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard in the northern California region, which includes San Francisco.

SCOPE AND LIMITATIONS

The methodology used to make this map is based on earthquake ground-shaking estimates, geologic material-strength characteristics and slope gradient. These data are gathered primarily from a variety of outside sources; thus the quality of the data is variable. Although the selection of data used in this evaluation was rigorous, the State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data gathered from outside sources.

Earthquake-induced landslide zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, these zone maps identify areas where the potential for earthquake-induced landslides is relatively high. Earthquake-generated ground failures that are not addressed by this map include those associated with ridge-top spreading and shattered ridges. No attempt has been made to map potential run-out areas of triggered landslides. It is possible that such run-out areas may extend beyond the zone boundaries. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, is not specifically addressed by the earthquake-induced landslide zone or this report. See Section 1, Liquefaction Evaluation Report for the southern part of San Francisco and DeLisle (1997) for the Liquefaction Evaluation Report for the northern part, for more information on the delineation of liquefaction zones.

Information developed in the study is presented in two parts: physiographic, and geologic conditions in PART I, and ground shaking opportunity, landslide hazard potential and zoning evaluations in PART II.

PART I

STUDY AREA LOCATION AND PHYSIOGRAPHY

San Francisco encompasses 49-square-miles and is located in the western part of the Coast Ranges along the central California coast. The city spreads across a peninsula bound by the Pacific Ocean on the west and San Francisco Bay on the north and east. The prominent northwesterly structural and topographic trend of the northern Coast Ranges is not evident in the city except for minor hills and valleys. The present topography is the result of erosion of Mesozoic Franciscan Complex rocks of varying hardness with deposits of windblown sand that mantle the bedrock exposures. Quaternary tectonism, marine and estuarine deposition, and artificial fill (man-made land) have also contributed to the development of the current topographic setting of the study area.

San Francisco is accessible from the north on US Highway 101 across the Golden Gate Bridge, from the east on Interstate Highway 80 across the Bay Bridge, and from the south on US Highway 101 and Interstate Highway 280. Land use in the city varies from densely urban in the northeast to a multilevel residential setting elsewhere. Scattered across the city are several parks, the largest of which is Golden Gate Park in the west-central part of the city.

GEOLOGIC CONDITIONS

Surface and Bedrock Geology

The northern parts of San Francisco are included on the southern portion of the San Francisco North, Point Bonita, and western portion of the Oakland West 7.5-minute quadrangles. These quadrangles have been mapped in detail by Schlocker (1974; San Francisco North and Point Bonita) and Radbruch (1957; Oakland West). Blake and others (in press) have updated the geologic maps for these areas in digital form. The southern parts of San Francisco are included in the northern portion of the San Francisco South and Hunters Point quadrangles, which were originally mapped by Bonilla (1971) and recently digitally updated (Bonilla, 1998). The geologic mapping was briefly field checked during this study. Observations were made of exposures, aspects of weathering, and general surface expression of the geologic units. In addition, the relation of the various geologic units to development and abundance of landslides was noted.

The bedrock consists of Cretaceous (K) and/or Jurassic (J) Franciscan Complex rocks, which accumulated in three distinct accreted terranes or structural assemblages. These are, from west to east, the San Bruno Mountain terrane; the Marin Headlands terrane; and the Alcatraz terrane (Blake and others, in press). The Franciscan Complex is subdivided into lithologic units of: serpentinite (labeled sp on the geologic maps); harder, massive serpentinite and peridotite (Jspm), greenstone (KJg, Jfg, and Jfgs); chert (KJc and KJfch); massive graywacke sandstone (Kfss and Kfgwy); massive sandstone containing more than two-percent potassium feldspar (KJsk); shale with some sandstone interbeds (Kfsh); and interbedded sandstone and shale (KJs, Kfs, and fs). Two northwest-trending shear zones, consisting of indistinguishable, sheared rock units (KJu and fsr), separate the three accreted terranes.

The late Pliocene to Pleistocene Merced Formation (QTm), located primarily in the southwestern portion of San Francisco, consists of sand, silt, and clay basin deposits that originated in a shallow marine and coastal non-marine setting. As this basin was uplifted, the Pleistocene Colma Formation (Qc) was deposited unconformably on the Merced Formation and more extensively across the northwestern and central part of the city (Wahrhaftig and Sloan, 1989). The Qc consists of fine to medium sand with lesser beds of sandy silt, clay, and gravel. Other surficial deposits of the city consist of: rubbly slope debris and ravine fill (Qsr); old beach deposits (Oob); dune deposits (Qd); alluvium (Qal); bay mud (Qm); recent beach deposits (Qb and Qs); undifferentiated sedimentary deposits (Qu); landslides (Ql); and artificial fill (Qaf). These units were deposited on the old topographic surface of Franciscan Complex rocks. The Qsr generally surrounds the elevated bedrock outcrops. The Qd is prominent in the northern and central portions of the city and the Qu is located in the eastern part of the city. Additional information pertaining to the Quaternary deposits is presented in Section 1, the Liquefaction Evaluation Report, and in DeLisle (1997).

Although landslide deposits were found throughout the city, they were found in greater frequency associated with the oversteepened slopes along the northern and western shoreline as well as in some inland upland areas. Of all of the geologic units, the Merced Formation (QTm) appears to have a greater abundance of landslides associated with it than other units.

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, they first must be ranked based on their overall shear strength. Shear strength data for the rock units identified on the geologic map were obtained from the City and County of San Francisco, Department of Building Inspection geotechnical files (see Appendix A). The locations of rock and soil samples taken for shear testing are shown on Plate 2.1.

Shear strength data gathered from the above source were compiled for each mapped geologic unit, and subdivided for fine-grained and coarse-grained lithologies if appropriate. Geologic units were grouped on the basis of average angle of internal friction (average f) and lithologic character. To subdivide mapped geologic formations that have both fine-grained and coarse-grained lithologies, we assumed that where stratigraphic bedding dips into a slope (favorable bedding) the coarse-grained material strength dominates, and where bedding dips out of a slope (adverse bedding) the fine-grained material strength dominates. We then used structural information from the geologic map (see "Structural Geology") and terrain data in the form of slope gradient and aspect, to identify areas with a high potential for containing adverse bedding conditions. These areas, located on the map, were then used to modify the geologic material-strength map to reflect the anticipated lower shear strength for the fine-grained materials.

In addition, geologic formations that are represented by different geologic symbols on the two geologic maps for San Francisco, north and south, have been combined for the statistical analysis. These formations are KJc-KJfch and Kfs-KJs.

The results of the grouping of geologic materials in San Francisco are in Tables 2.1 and 2.2.

CITY AND COUNTY OF SAN FRANCISCO
SHEAR STRENGTH GROUPS

	Formation Name* (rock types)	Number Tests	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group C (psf)	No data but Similar Lithology	Phi Values Used in Stability Analyses
GROUP 1	KJc-KJfch(fbc)	3	36/30	36/35	399/200	gb, fs(fbc)	36
	Kfsh(fbc)	5	36/36			Jspm, KJg	
	Kfss(fbc)	3	38/31			Jfg, Jfgs	
	Kfs-KJs(fbc)	12	35/33			KJsk(fbc)	
	Qc	65	35/35			Kfgwy(fbc)	
	Qd	134	36/37			Qob	
GROUP 2	sp	46	31/32	30/31	815/620	fsr(fbc)	30
	KJu(fbc)	3	30/30			Qb	
	Qsr	57	30/32			Qs	
	Qu	105	30/30				
GROUP 3	Qaf	49	27/26	27/26	693/420	QTm	27
GROUP 4	KJc-KJfch(abc)	6	22/23	22/22	1366/800	fs(abc)	22
	KJsk(abc)	2	21/21				
	Kfsh(abc)	12	22/22				
	Kfss(abc)	5	21/21				
	Kfs-KJs(abc)	41	21/23				
	Kfgwy(abc)	1	22/22				
	KJu(abc)	3	21/20				
	fsr(abc)	4	22/22				
GROUP 5	Qm	9	16/15	16/15	465/400		16
GROUP 6	Qls	9	11/11	11/11	693/700		11

*abc = adverse bedding condition, fine-grained material strength
*fbc = favorable bedding condition, coarse-grained material strength

Table 2.1. Summary of the Shear Strength Statistics for the City and County of San Francisco.

SHEAR STRENGTH GROUPS FOR THE CITY AND COUNTY OF SAN FRANCISCO					
GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**	**GROUP 5**	**GROUP 6**
Jspm, KJg	sp	QTm	fs(abc)	Qm	Qls
Jfg, Jfgs	KJu(fbc)	Qaf	KJc-KJfch(abc)		
gb, fs(fbc)	fsr(fbc)		KJsk(abc)		
KJc-KJfch(fbc)	Qsr		Kfgwy(abc)		
KJsk(fbc)	Qu		Kfss(abc)		
Kfgwy(fbc)	Qd		Kfsh(abc)		
Kfss(fbc)	Qs		Kfs-KJs(abc)		
Kfsh(fbc)			KJu(abc)		
Kfs-KJs(fbc)			fsr(abc)		
Qc, Qob, Qd					

Table 2.2. Summary of the Shear Strength Groups for the City and County of San Francisco.

The large number of landslides observed within the Merced Formation (QTm) in the southwestern portion of San Francisco and to the south in Daly City (Bonilla, 1971), along with the description by Ellen and Wentworth (1995) that weathered QTm is relatively weak, led to the inclusion of this unit in shear strength Group 3 (phi = 27 degrees).

According to statistical protocol, if there are fewer than 30 shear strength tests for a particular formation the median value, instead of the mean, should be used to represent the formation when forming shear strength groups. There is a disparity between the mean and median value for the rock formations KJc-KJfch(fbc), Kfss (fbc), and Kfs-KJs(fbc) that would normally lead to the formation of a new shear strength group or moving them from Group 1 to Group 2. However, they have been added to the stronger Group 1 because of the similarity in observed field characteristics to other formations in Group 1, and the relative lack of landslides found in these formations.

Structural Geology

Using the geologic structural data, including bedding and foliation attitudes (strike and dip) and fold axes, from the geologic maps by Schlocker (1974), Radbruch (1957), and Bonilla (1971), areas of common stratigraphic dip direction and magnitude were categorized and digitized, using a method similar to that presented by Brabb (1983). The dip direction category was compared to the slope aspect (direction) category and, if the same, the dip magnitude and slope gradient categories were compared. If the dip magnitude category was less than or equal to the slope gradient category, and the bedding dip was greater than 25% (4:1 slope), the area was marked as a potential adverse bedding area. This information was then used to subdivide mapped geologic units into areas where fine-grained and coarse-grained strengths would be used.

Landslide Inventory

The evaluation of earthquake-induced landsliding requires an up-to-date and complete picture of the previous occurrence of landsliding. An inventory of existing landslides in San Francisco was prepared by reviewing published landslide inventories and combining field observations, analysis of aerial photos, and interpretation of landforms on current and older topographic maps.

Published maps and reports showing or discussing landslides, such as Schlocker (1974), Blake and others (1974), Radbruch (1957), and URS/John A. Blume and Associates (1974), were evaluated during the production of the landslide inventory for this study. In addition, there are a number of landslides that have been included in the inventory that were caused or reactivated during the 1906 San Francisco and 1989 Loma Prieta earthquakes (Lawson and others, 1908; Youd and Hoose, 1978; Seed and others, 1990; Keefer and Manson, 1998).

Stereo-paired, black-and-white aerial photos purchased from WAC Corporation of Eugene, Oregon were used for landslide interpretation (see Air Photos in References). These photos are dated 4-27-96 and are at a scale of 1:24,000. The photos were examined using a mirror stereoscope at 1.5x, 3x, and 8x magnification. Due to the amount of land modification and construction in San Francisco, many landslides are covered or modified and, therefore, difficult to identify using conventional techniques. For this reason, landslides identified in geotechnical reports on file with the San Francisco Department of Building Inspection were included in our inventory.

The completed hand-drawn landslide map was scanned and digitized. The database was populated with information on each landslide, including confidence of interpretation (definite, probable, or questionable), activity (active, dormant, or relict), estimated thickness and associated geologic unit(s). The landslide inventory map is included with Plate 2.1.

PART II

EARTHQUAKE-INDUCED LANDSLIDE GROUND SHAKING OPPORTUNITY

Design Strong-Motion Record

The Newmark analysis used in delineating the earthquake-induced landslide zones requires the selection of a design earthquake strong-motion record. Although the San Andreas Fault Zone does not cross any portion of the City, it is clearly the dominant source for strong ground shaking within San Francisco. The selection of a strong-motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA). The parameters were estimated from maps prepared by DMG for a 10% probability of being exceeded in 50 years (Petersen and others, 1996; Cramer and Petersen, 1996). The parameters used in the record selection are:

Modal Magnitude:	7.7 to 7.9
Modal Distance:	3.6 to 13.0 km
PGA:	0.52 to 0.93 g

A suitable strong-motion record that precisely fits these parameters could not be found. The Southern California Edison Lucerne record from the 1992 7.3-magnitude Landers, California, earthquake was used because it was the closest fit to the above criteria. This record had a source to recording site distance of 1.1 km and a PGA of 0.80 g. The selected strong-motion record was not scaled or otherwise modified prior to analysis.

Displacement Calculation

To develop a relationship between the yield acceleration (a_y; defined as the horizontal ground acceleration required to cause the factor of safety to equal 1.0) and Newmark displacements, the design strong-motion record was integrated twice for a given a_y to find the corresponding displacement, and the process repeated for a range of a_y (Jibson, 1993). The resulting curve in Figure 2.1 represents the full spectrum of displacements that can be expected for any combination of geologic material strength and slope angle, as represented by the yield acceleration. We used displacements of 30, 15 and 5 cm as criteria for rating levels of earthquake shaking damage on the basis of the work of Youd (1980), Wilson and Keefer (1983), and the DMG pilot study for earthquake-induced landslides (McCrink and Real, 1996). Applied to the curve in Figure 2.1, these displacements correspond to yield accelerations of 0.148, 0.182, and 0.243 g. These yield acceleration values were then used as earthquake-induced landslide susceptibility criteria in the stability analyses.

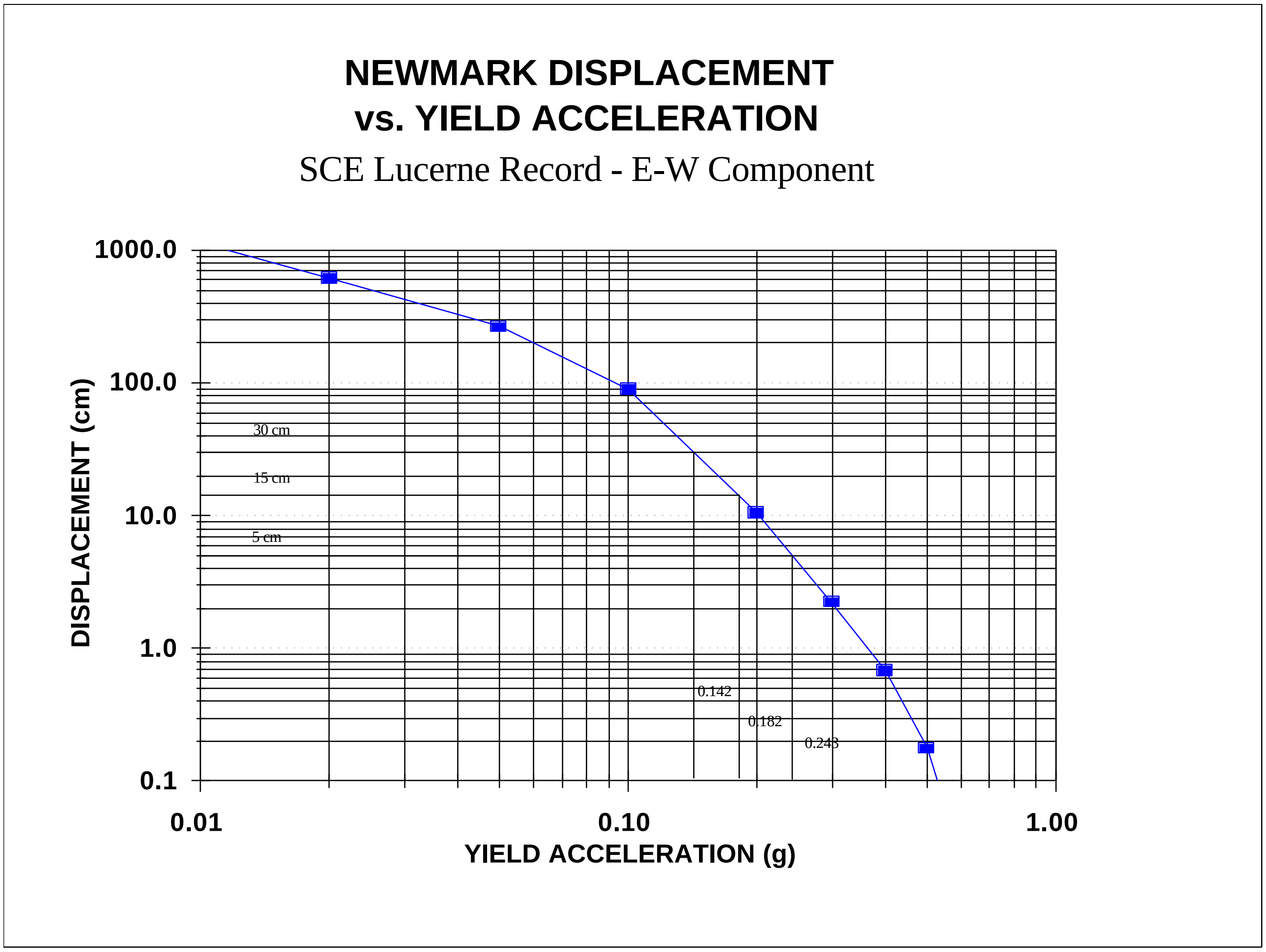


Figure 2.1. Yield Acceleration vs. Newmark Displacement for the Southern California Edison Lucerne strong-motion record from the 28 June 1992 Landers, California earthquake.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. A set of digital terrain files was obtained from the City to calculate slope gradient for the terrain within San Francisco. These files contained digitized contours, breaklines, and spot elevations that were collected from stereo-pair aerial photography flown in September and October 1993. These files were translated into a format usable by DMG and converted first to a triangular-irregular-network (TIN) computer model, and then into a regularly-spaced digital elevation model (DEM). The resulting DEM has a 10-meter horizontal resolution. Vertical accuracy is estimated to be on the order of 1 to 2 meters.

A slope map was made from the corrected DEM using a third-order, finite difference, center-weighted algorithm (Horn, 1981). The DEM was then used to make a slope-aspect map. The slope map was used first in conjunction with the aspect map and geologic structural data to identify areas of potential adverse bedding conditions, and then again with the geologic strength map in the preparation of the earthquake-induced landslide hazard potential map.

Stability Analysis

A slope stability analysis was performed for each geologic material strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation:

$$a_y = (FS - 1)g \sin \alpha$$

where FS is the Factor of Safety, g is the acceleration due to gravity, and α is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure α is the same as the slope angle.

The yield acceleration calculated by Newmark's equations represents the susceptibility to earthquake-induced failure of each geologic material strength group for a range of slope gradients. The acceleration values were compared with the ground shaking opportunity, defined by Figure 2.1, to determine the earthquake-induced landslide hazard potential. Based on the criteria described in Figure 2.1 above, if the calculated yield acceleration was less than 0.142 g expected displacements could be greater than 30 cm, and a HIGH (H on Table 2.3) hazard potential was assigned. Likewise, if the calculated a_y fell between 0.142 and 0.182 g a MODERATE (M on Table 2.3) hazard potential was assigned, between 0.182 and 0.243 g a LOW (L on Table 2.3) potential was assigned, and if a_y were greater than 0.243 g a VERY LOW (VL on Table 2.3) potential was assigned.

Table 2.3 summarizes the results of the stability analyses. The earthquake-induced landslide hazard potential map was prepared by combining the geologic material-strength map and the slope map according to this table.

CITY OF SAN FRANCISCO

HAZARD POTENTIAL MATRIX

GEOLOGIC MATERIAL GROUP	MEAN PHI	SLOPE CATEGORY (% SLOPE) I 0 to 5%	II 6 to 10%	III 11 to 15%	IV 16 to 22%	V 23 to 26%	VI 27 to 32%	VII 33 to 37%	VIII 38 to 46%	IX 47 to 57%	X >58%
1	36	VL	VL	VL	VL	VL	VL	VL	VL	L	H
2	30	VL	VL	VL	VL	VL	VL	L	M	H	H
3	27	VL	VL	VL	VL	VL	L	M	H	H	H
4	22	VL	VL	VL	L	M	H	H	H	H	H
5	16	VL	L	M	H	H	H	H	H	H	H
6	11	H	H	H	H	H	H	H	H	H	H

Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in San Francisco. Shaded area indicates hazard potential levels included within the hazard zone.

EARTHQUAKE-INDUCED LANDSLIDE ZONE

Criteria for Zoning

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (1996). Under those criteria, earthquake-induced landslide zones are areas meeting one or both of the following:

1. Areas identified as having experienced landslide movement in the past (including all mappable landslide deposits and source areas), and, where possible, areas known to have experienced earthquake-induced landsliding during historic earthquakes.

2. Areas where geologic and geotechnical data and analyses indicate that the earth materials may be susceptible to earthquake-induced slope failure.

Existing Landslides

Studies of the types of landslides caused by earthquakes (Keefer, 1984) show that re-activation of the whole mass of deep-seated landslide deposits is rare. However, it has been observed that the steep scarps and toe areas of existing landslides, which formed as a result of previous landslide movement, are particularly susceptible to earthquake-induced slope failure. In addition, because they have been disrupted during landslide movement, landslide deposits are inferred to be weaker than coherent, undisturbed, adjacent source rocks. Finally, we felt that a long duration, San Andreas fault-type earthquake could be capable of initiating renewed movement in existing deep-seated landslide deposits. Therefore, all existing landslides identified in the inventory with a definite or probable confidence of interpretation were included in the hazard zone.

Geologic and Geotechnical Analysis

On the basis of a DMG pilot study (McCrink and Real, 1996) the earthquake-induced landslide zone includes all areas determined to lie within the High, Moderate and Low levels of hazard potential. Therefore, as shown in Table 2.3, geologic strength group 6 is always included in the zone (mapped landslides); strength group 5 above 5%; strength group 4 above 15%; strength group 3 above 26%; strength group 2 above 32%; and strength group 1, the strongest rock types, were zoned for slope gradients above 46%. This results in roughly 3% of the land in the City lying within the hazard zone.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project. Hanson Tom, Kung-Kay Chiu, Susan Yee, Zan Turner, and their staffs at the City and County of San Francisco were helpful in gathering rock strength and landslide inventory information. Jeffery Johnson and George White aided in the acquisition of the City's digital terrain, orthophotos, and street/parcel files. Russ Graymer of the U.S. Geological Survey provided the preliminary digital geologic maps for the City.

REFERENCES

Blake, M.C., Jr., Bartow, J.A., Frizzel, V.A., Jr., Schlocker, J., Sorg, D., Wentworth, C. M. and Wright, R. H., 1974, Preliminary geologic map of Marin and San Francisco counties and Parts of Alameda, Contra Costa and Sonoma counties, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-574, scale 1:62,500.

Blake, M.C., Jr., Graymer, R.W. and Jones, D.L., in press, Digital geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma counties, California: U.S. Geological Survey Miscellaneous Field Studies Report and Map, scale unknown.

Bonilla, M.G., 1971, Preliminary geologic map of the San Francisco South Quadrangle and part of the Hunters Point Quadrangle, California: U.S. Geological Survey, Miscellaneous Field Studies Map, MF-0311, scale 1:24,000, two sheets.

Bonilla, M.G., 1998, Preliminary geologic map of the San Francisco South 7.5-minute Quadrangle and part of the Hunters Point 7.5-minute Quadrangle, San Francisco Bay Area, California: A Digital Database: U.S. Geological Survey Open-File Report 98-354, scale 1:24,000.

Brabb, E.E., 1983, Map showing direction and amount of bedding dip of sedimentary rocks in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1257C, 1 sheet, scale 1:62,500.

California State Mining and Geology Board, 1996, Criteria for delineating earthquake-induced landslide hazard zones: Unpublished California State Mining and Geology Board document developed by the Seismic Hazards Mapping Act Advisory Committee.

California State Mining and Geology Board, 1997, Guidelines for evaluating and mitigating seismic hazards in California: California Department of Conservation, Division of Mines and Geology, Special Publication 117, 74 p.

Cramer, C.H. and Petersen, M.D., 1996, Predominant seismic source distance and magnitude maps for Los Angeles, Orange and Ventura counties, California: Bulletin of the Seismological Society of America, v. 85, no. 5, pp. 1645-1649.

DeLisle, M.J., 1997, Seismic hazard evaluation of the south half of the San Francisco North and part of the Oakland West 7.5-minute quadrangles, San Francisco County, California: California Department of Conservation, Division of Mines and Geology, Open-File Report 97-05, 35 p.

Ellen, S.D. and Wentworth, C.M., 1995, Hillside materials and slopes of the San Francisco Bay Region, California: U.S. Geological Survey Professional Paper 1357, 215 p.

Horn, B.K.P., 1981, Hill shading and the reflectance map: Proceedings of the IEEE, v. 69, no. 1, p. 14-47.

Jibson, R.W., 1993, Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis: Transportation Research Board, National Research Council, Transportation Research Record 1411, 17 p.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406-421.

Keefer, D.K. and Manson, M.W., 1998, Regional distribution and characteristics of landslides generated by the earthquake *in* Keefer, D.K., *editor*, The Loma Prieta, California, Earthquake of October 17, 1989 – Landslides: U.S. Geological Survey Professional Paper 1551-C, pp. C7-C32.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906; report of the State Earthquake Investigation Commission: Carnegie Institution of Washington, Publication 87, v. 1 and atlas, 451 p.

McCrink, T.P. and Real, C.R., 1996, Evaluation of the Newmark method for mapping earthquake-induced landslide hazards in the Laurel 7-1/2 minute Quadrangle, Santa Cruz County, California: California Division of Mines and Geology Final Technical Report for U.S. Geological Survey Contract 143-93-G-2334, U.S. Geological Survey, Reston, Virginia, 31 p.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: Geotechnique, v. 15, no. 2, p. 139-160.

Petersen, M.D., Cramer, C.H., Bryant, W.A., Reichle, M.S. and Toppozada, T.R., 1996, Preliminary seismic hazard assessment for Los Angeles, Ventura, and Orange counties, California, affected by the January 17, 1994 Northridge earthquake: Bulletin of the Seismological Society of America, v. 86, no. 1B, p. S247-S261.

Radbruch, D. H., 1957, Areal and Engineering Geology of the Oakland West Quadrangle, California: U. S. Geological Survey Miscellaneous Geologic Investigations Map I-239, scale 1:24,000.

Schlocker, J., 1974, Geology of the San Francisco North Quadrangle, California: U. S. Geological Survey Professional Paper 782, 109p.

Seed, R.B., Dickenson, S.E., Reimer, M.F., Bray, J.D., Sitar, Nicholas, Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, Alan, Harder, L.F., Jr. and Power, M.S., 1990, Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake: University of California, Berkeley, Earthquake Engineering Research Center Report UCB/EERC-90/05, 137 p.

Smith, T.C., 1996, Preliminary maps of seismic hazard zones and draft guidelines for evaluating and mitigating seismic hazards: California Geology, v. 49, no. 6, p. 147-150.

URS/John A. Blume and Associates, 1974, San Francisco Seismic Safety Investigation: City and County of San Francisco Department of City Planning.

Wilson, R.C. and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877.

Wahrhaftig, Clyde and Sloan, Doris, editors, 1989, Geology of San Francisco and vicinity: American Geophysical Union, Field Trip Guidebook T105, 69 p.

Youd, T.L., 1980, Ground failure displacement and earthquake damage to buildings: American Society of Civil Engineers Conference on Civil Engineering and Nuclear Power, 2d, Knoxville, Tennessee, 1980, v. 2, p. 7-6-2 to 7-6-26.

Youd, T.L., and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, 177 p.

AIR PHOTOS

WAC Corporation, Inc., dated 4-27-96, Flight or Serial number WAC-96CA, Photo numbers 16-14 to 16-19, 16-38 to 16-44, 16-76 to 16-81, 16-119 to 16-125, scale 1:24,000.

APPENDIX A
SOURCE OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City and County of San Francisco, Department of Building Inspection	**574**

SECTION 3
GROUND SHAKING EVALUATION REPORT

Potential Ground Shaking in the City and County of San Francisco, California

By

Mark D. Petersen, Chris H. Cramer, Geoffrey A. Faneros, Charles R. Real, and Michael S. Reichle

California Department of Conservation
Division of Mines and Geology

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, Division of Mines and Geology (DMG) to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the Seismic Hazard Zone Maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (1997; also available on the Internet at http://www.consrv.ca.gov/dmg/pubs/sp/117/).

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included, are ground motion and related maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps provided herein are presented at a scale of approximately 1:150,000 (scale bar provided on maps), and show the full 7.5- minute quadrangle and portions of the adjacent eight quadrangles. They can be used to assist in the specification of earthquake loading conditions ***for the analysis of ground failure*** according to the "Simple Prescribed Parameter Value" method (SPPV) described in the site investigation guidelines (California State Mining and Geology Board, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard.

This section and Sections 1 and 2, addressing liquefaction and earthquake-induced landslide hazards, constitute a report series that summarizes development of seismic hazard zone maps in the state. Additional information on seismic hazard zone mapping in California can be accessed on DMG's Internet homepage:
http://www.consrv.ca.gov/dmg/shezp/

EARTHQUAKE HAZARD MODEL

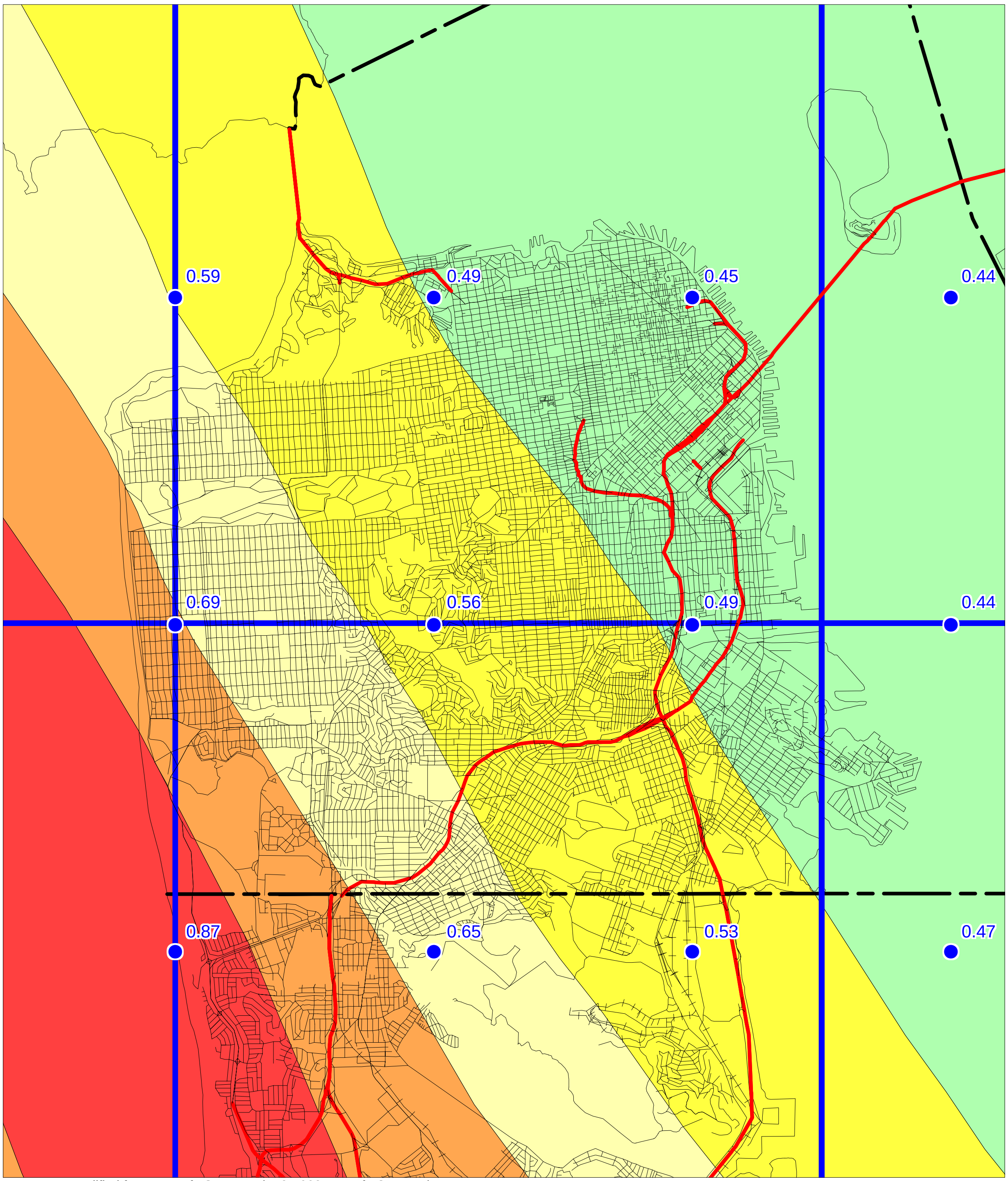
The estimated ground shaking is derived from the seismogenic sources as published in the statewide probabilistic seismic hazard evaluation released cooperatively by the California Department of Conservation, Division of Mines and Geology, and the U.S. Geological Survey (Petersen and others, 1996). That report documents an extensive 3-year effort to obtain consensus within the scientific community regarding fault parameters that characterize the seismic hazard in California. Fault sources included in the model were evaluated for long-term slip rate, maximum earthquake magnitude, and rupture geometry. These fault parameters, along with historical seismicity, were used to estimate return times of moderate to large earthquakes that contribute to the hazard.

The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). The published hazard evaluation of Petersen and others (1996) only considers uniform firm-rock site conditions. In this report, however, we extend the hazard analysis to include the hazard of exceeding peak horizontal ground acceleration (PGA) at 10% probability of exceedance in 50 years on spatially uniform conditions of rock, soft rock, and alluvium. These soil and rock conditions approximately correspond to site categories defined in Chapter 16 of the Uniform Building Code (ICBO, 1997), which are commonly found in California. We use the attenuation relations of Boore and others (1997), Campbell (1997), Sadigh and others (1997), and Youngs and others (1997) to calculate the ground motions.

The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10% probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. The sites where the hazard is calculated are represented as dots and ground motion contours as shaded regions. The quadrangle of interest is outlined by bold lines and centered on the map. Portions of the eight adjacent

THE CITY AND COUNTY OF SAN FRANCISCO

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)
1998
FIRM ROCK CONDITIONS



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1 2
Miles

Department of Conservation
Division of Mines and Geology

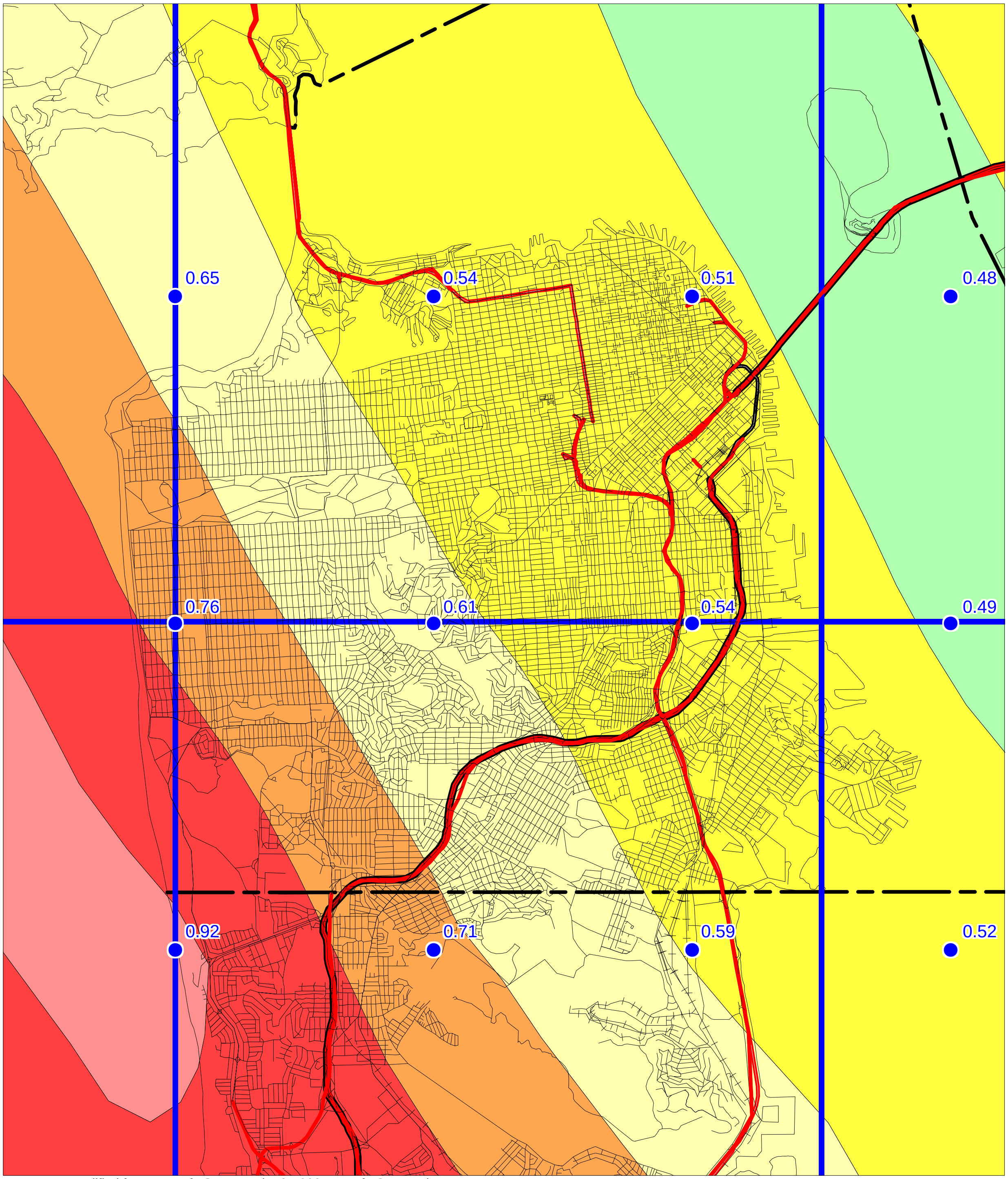
Figure 3.1

THE CITY AND COUNTY OF SAN FRANCISCO

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

SOFT ROCK CONDITIONS



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1 2
Miles

Department of Conservation
Division of Mines and Geology

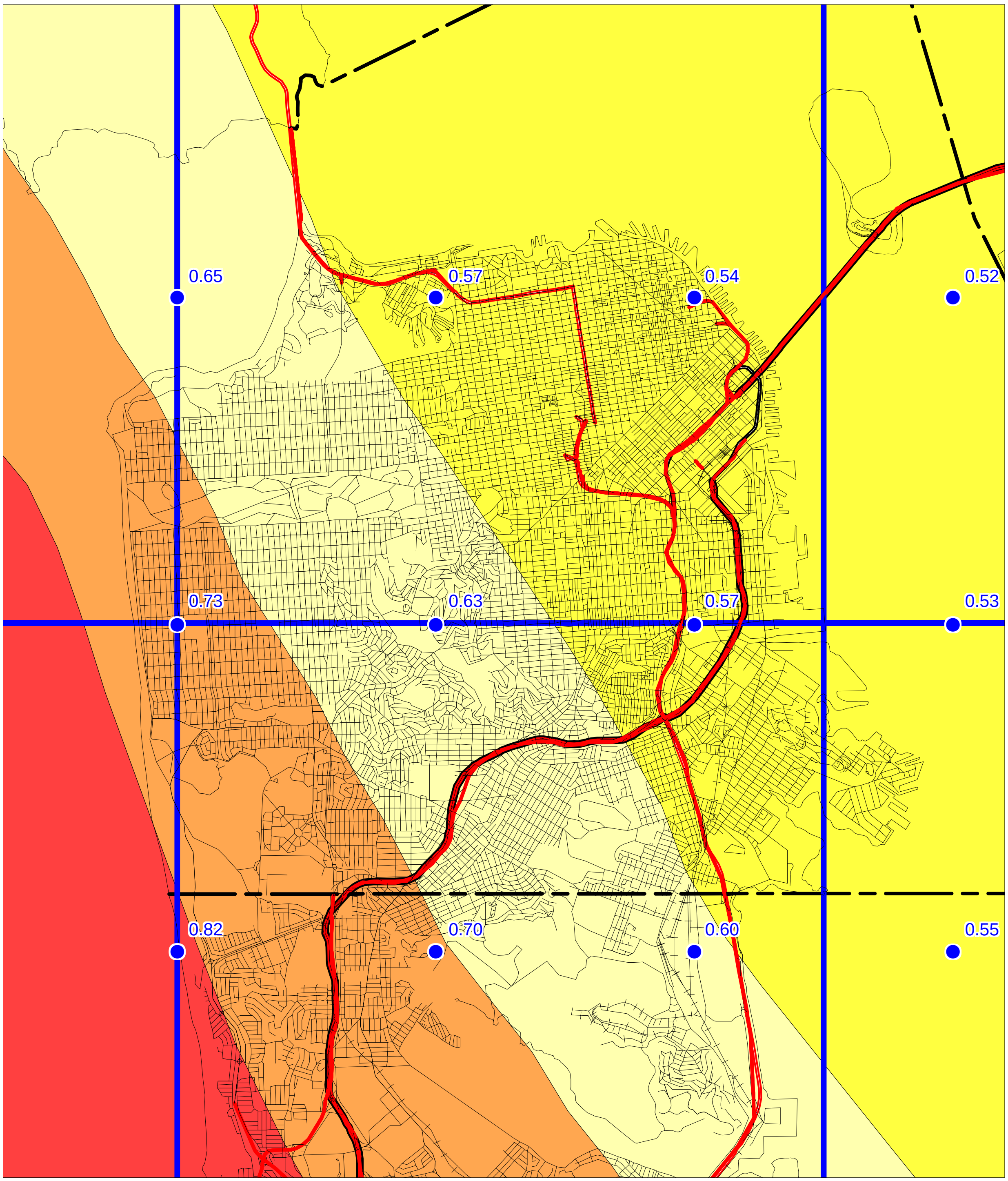
Figure 3.2

THE CITY AND COUNTY OF SAN FRANCISCO

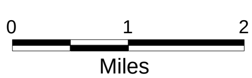
10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

ALLUVIUM CONDITIONS



Base map modified from MapInfo Street Works © 1998 MapInfo Corporation



Department of Conservation
Division of Mines and Geology

Figure 3.3

quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating ground motion values by selecting the map that matches the actual site conditions, and interpolating from the calculated values of PGA rather than the contours, since the points are more accurate.

APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS

Deaggregation of the seismic hazard identifies the contribution of each of the earthquakes (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (see Cramer and Petersen, 1996). The map in Figure 3.4 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10% probability of exceedance in 50 years on alluvial site conditions (*predominant earthquake*). This information gives a rationale for selecting a seismic record or ground motion level in evaluating ground failure. However, it is important to keep in mind that more than one earthquake may contribute significantly to the hazard at a site, and those events can have markedly different magnitudes and distances. For liquefaction hazard the predominant earthquake magnitude from Figure 3.4 and PGA from Figure 3.3 (alluvium conditions) can be used with the Youd and Idriss (1997) approach to estimate cyclic stress ratio demand. For landslide hazard the predominant earthquake magnitude and distance can be used to select a seismic record that is consistent with the hazard for calculating the Newmark displacement (Wilson and Keefer, 1983). When selecting the predominant earthquake magnitude and distance, it is advisable to consider the range of values in the vicinity of the site and perform the ground failure analysis accordingly. This would yield a range in ground failure hazard from which recommendations appropriate to the specific project can be made. Grid values for predominant earthquake magnitude and distance should **not** be interpolated at the site location, because these parameters are not continuous functions.

USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is ***not appropriate for site specific structural design applications***. Use of the ground motion maps prepared at larger scale is limited to estimating earthquake loading conditions for preliminary assessment of ground failure at a specific location. We recommend consideration of site-specific analyses before deciding on the sole use of these maps for several reasons.

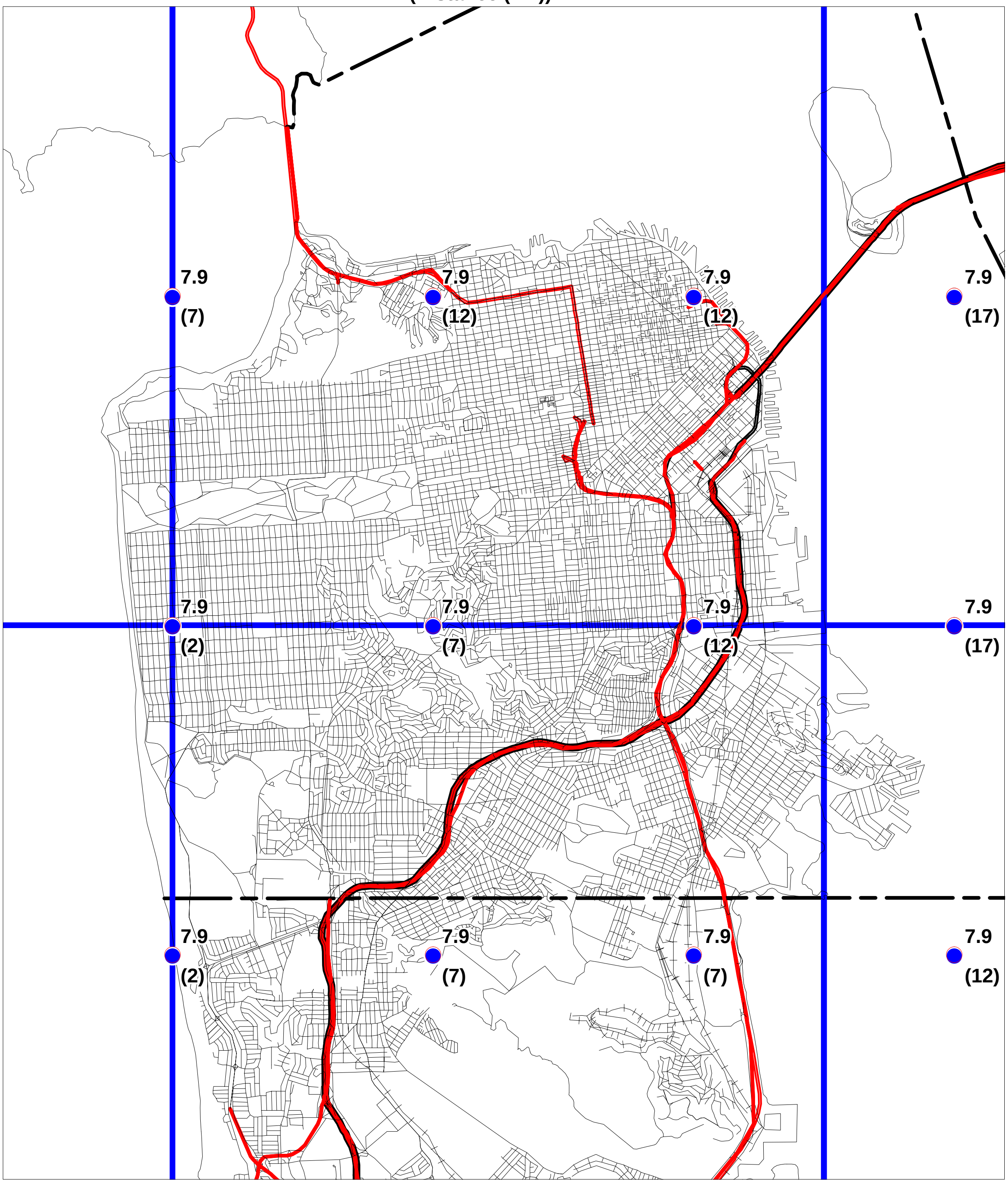
1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated hazard values may also differ by a similar amount. At a specific location, however, the log-linear attenuation

THE CITY AND COUNTY OF SAN FRANCISCO

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION

1998

PREDOMINANT EARTHQUAKE
Magnitude (Mw)
(Distance (km))



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1 2
Miles

Department of Conservation
Division of Mines and Geology

Figure 3.4

of ground motion with distance renders hazard estimates less sensitive to uncertainties in source location.

2. The hazard was calculated on a grid at sites separated by about 5 km (0.05 degrees). Therefore, the calculated hazard may be located a couple kilometers away from the site. We have provided shaded contours on the maps to indicate regional trends of the hazard model. However, the contours only show regional trends that may not be apparent from points on a single map. Differences of up to 2 km have been observed between contours and individual ground acceleration values. *We recommend that the user interpolate PGA between the grid point values rather than simply using the shaded contours*.

3. Uncertainties in the hazard values have been estimated to be about +/- 50% of the ground motion value at two standard deviations (Cramer and others, 1996).

4. Not all active faults in California are included in this model. For example, faults that do not have documented slip rates are not included in the source model. Scientific research may identify active faults that have not previously been recognized. Therefore, future versions of the hazard model may include other faults and omit faults that are currently considered.

5. A map of the predominant earthquake magnitude and distance is provided from the deaggregation of the probabilistic seismic hazard model. However, it is important to recognize that a site may have more than one earthquake that contributes significantly to the hazard. Therefore, in some cases earthquakes other than the predominant earthquake should also be considered.

Because of its simplicity, it is likely that the SPPV method (California State Mining and Geology Board, 1997) will be widely used to estimate earthquake shaking loading conditions for the evaluation of ground failure hazards. It should be kept in mind that ground motions at a given distance from an earthquake will vary depending on site-specific characteristics such as geology, soil properties, and topography, which may not have been adequately accounted for in the regional hazard analysis. Although this variance is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1, 3.2, and 3.3, extreme deviations can occur. More sophisticated methods that take into account other factors that may be present at the site (site amplification, basin effects, near source effects, etc.) should be employed as warranted. The decision to use the SPPV method with ground motions derived from Figures 3.1, 3.2, or 3.3 should be based on careful consideration of the above limitations, the geotechnical and seismological aspects of the project setting, and the “importance” or sensitivity of the proposed building with regard to occupant safety.

REFERENCES

Boore, D.M., Joyner, W.B. and Fumal, T.E., 1997, Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra: Seismological Research Letters, v. 68, p. 154-179.

California State Mining and Geology Board, 1997, Guidelines for evaluating and mitigating seismic hazards in California: California Department of Conservation, Division of Mines and Geology, Special Publication 117, 74 p.

Campbell, K.W., 1997, Attenuation relationships for shallow crustal earthquakes based on California strong motion data: Seismological Research Letters, v. 68, p. 180-189.

Cramer, C.H. and Petersen, M.D., 1996, Predominant seismic source distance and magnitude maps for Los Angeles, Orange and Ventura counties, California: Bulletin of the Seismological Society of America, v. 85, no. 5, p. 1645-1649.

Cramer, C.H., Petersen, M.D. and Reichle, M.S., 1996, A Monte Carlo approach in estimating uncertainty for a seismic hazard assessment of Los Angeles, Ventura, and Orange counties, California: Bulletin of the Seismological Society of America, v. 86, p. 1681-1691.

International Conference of Building Officials (ICBO), 1997, Uniform Building Code: v. 2, Structural engineering and installation standards, 492 p.

Jennings, C.W., *compiler*, 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, California Geologic Data Map Series, map no. 8.

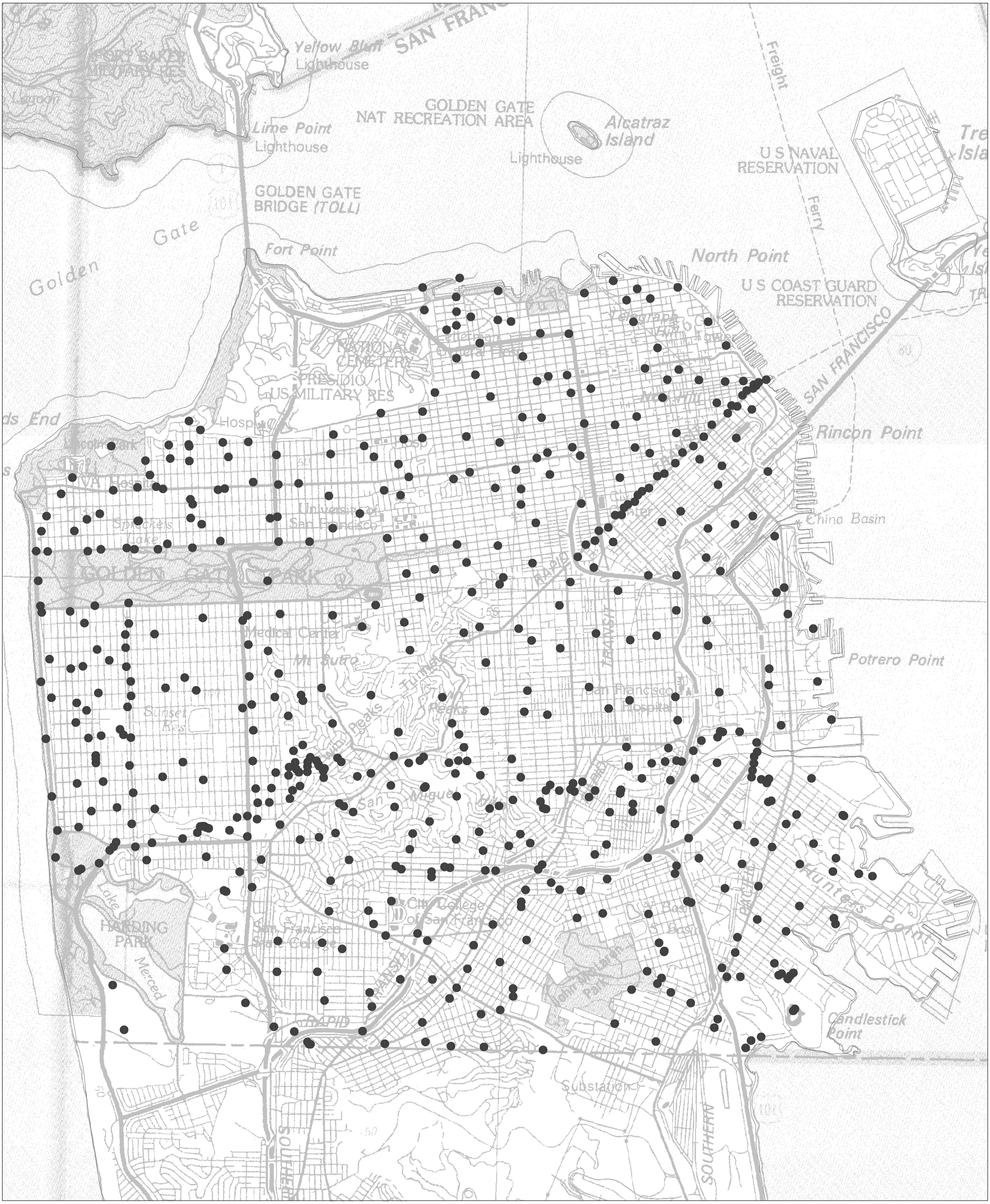
Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology Open-File Report 96-08; also U.S. Geological Survey Open-File Report 96-706, 66 pp.

Sadigh, K., Chang, C.-Y., Egan, J.A., Makdisi, F. and Youngs, R.R., 1997, SEA96- A new predictive relation for earthquake ground motions in extensional tectonic regimes: Seismological Research Letters, v. 68, p. 190-198.

Wilson, R.C. and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, Earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877.

Youd, T.L. and Idriss I.M., 1997, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: Technical Report NCEER-97-0022, 40 p.

Youngs, R.R., Chiou, S.-J., Silva, W.J. and Humphrey, J.R., 1997, Stochastic point-source modeling of ground motions in the Cascadia Region: Seismological Research Letters, v. 68, p. 74-85.



Base map enlarged from U.S.G.S. 30 x 60–minute series

Plate 1.1 Borehole log data locations, city and county of San Francisco.

ONE MILE

SCALE

Base map enlarged from U.S.G.S. 30 x 60-minute series

Plate 1.2 Historically highest ground water contours, city and county of San Francisco.

X Site of historical earthquake-generated liquefaction. See "Areas of Past Liquefaction" discussion in text.

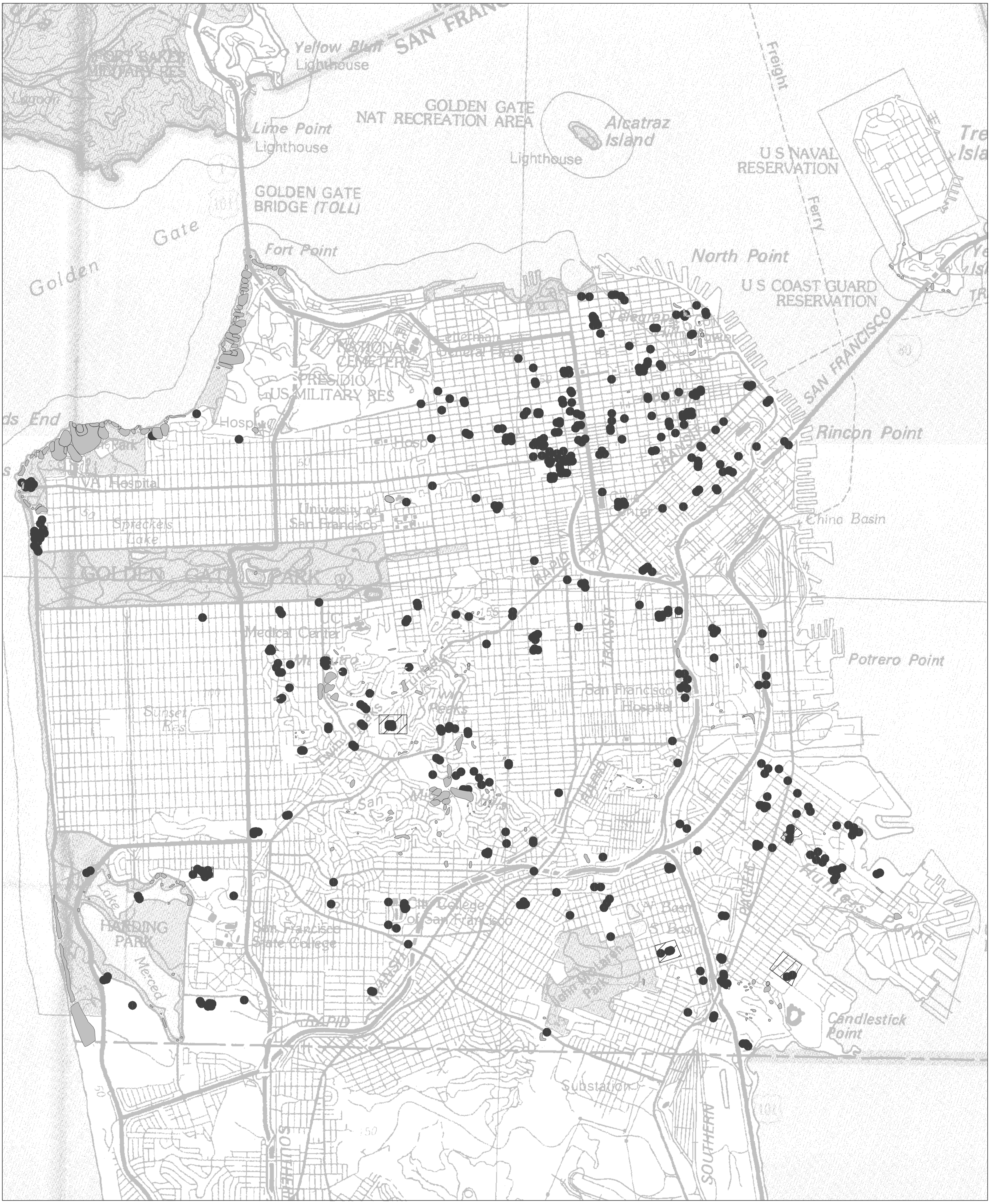
Bedrock

30 Depth to ground water in feet

10'-30' Generalized ground-water levels

ONE MILE

SCALE



Base map enlarged from U.S.G.S. 30 x 60–minute series

Plate 2.1 Landslide Inventory, and Shear Test Sample Locations, City and County of San Francisco.

shear test sample location landslide tract report with multiple borings

ONE MILE

SCALE